A Compact, High-Performance Continuous Magnetic Refrigerator

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ABSTRACT

We present test results of the first adiabatic demagnetization refrigerator (ADR) that can produce continuous cooling at sub-kelvin temperatures. This system uses multiple stages that operate in sequence to cascade heat from a "continuous" stage up to a heat sink. Continuous operation avoids the usual constraints of long hold times and short recycle times that lead to the generally large mass of single-shot ADRs, and allows us to achieve much higher cooling power per unit mass. Our design goal is 10 μW of cooling at 50 mK while rejecting heat to a 6-10 K heat sink. The total cold mass is estimated to be less than 10 kg, including magnetic shielding of each stage. These parameters envelop the requirements for currently planned astronomy missions. The relatively high heat rejection capability allows it to operate with a mechanical cryocooler as part of a cryogen-free, low temperature cooling system. This has the advantages of long mission life and reduced complexity and cost. At present, we have assembled a three-stage ADR that operates with a superfluid helium bath. Additional work is underway to develop magnetocaloric materials that can extend its heat rejection capability up to 10 K. This paper discusses the design and operation of the ADR, as well as interface requirements for cryocooler-based operation.

INTRODUCTION

Nearly all adiabatic demagnetization refrigerators that have been built since their introduction in the 1920s have been single-shot systems. This is a natural consequence of the way ADRs produce cooling: the cycle consists of discrete steps in which the solid refrigerant is magnetized, the heat generated is reject to a heat sink through a heat switch, the refrigerant is then thermally isolated (i.e. the heat switch is opened), and finally the refrigerant is demagnetized to cool it to operating temperature. The systems which have been designed to operate continuously, such as the rotating-wheel concept, use techniques which prevent them from cooling below 1 K. So for sub-Kelvin temperatures, single-shot operation has been the norm, and since size of a single-shot refrigerator scales up with heat load and hold time, ADRs tend to have relatively large mass and low cooling power. This is particularly true for systems operating at temperatures near and below 60 mK where the heat capacity of the refrigerant declines rapidly with temperature. Since this is the preferred operating range for many upcoming space missions, and many of these missions will use large format detector arrays with significantly higher power dissipation, there is a growing need for more capable ADRs. We have begun developing a system[1] that can operate continuously whose cooling power per unit mass is much higher than single-shot systems can achieve. Its design also allows it reject its heat at higher temperature, as high as 6-10 K, so that it can be mated to a mechanical cryocooler. For space missions, this opens up the possibility of flying cryogen-free systems with much lower overall mass and much longer mission lifetimes.

The continuous ADR (CADR) uses multiple stages to achieve continuous cooling. Each stage consists of a solid magnetic refrigerant (salt pill), a magnet, and a heat switch. A three-stage

CADR is shown schematically in Figure 1. The "continuous" stage is directly connected to the load and is magnetized or demagnetized, as needed, to maintain constant temperature. The remaining stages act to periodically cascade heat from the continuous stage up to the heat sink. This is accomplished by cooling each stage to a temperature lower than that of the adjacent lower stage, closing the heat switch, and transferring heat until the lower stage's magnet is fully charged. This is done first to recycle the continuous stage, then for each stage in sequence until the last stage is magnetized to reject its heat to the sink.

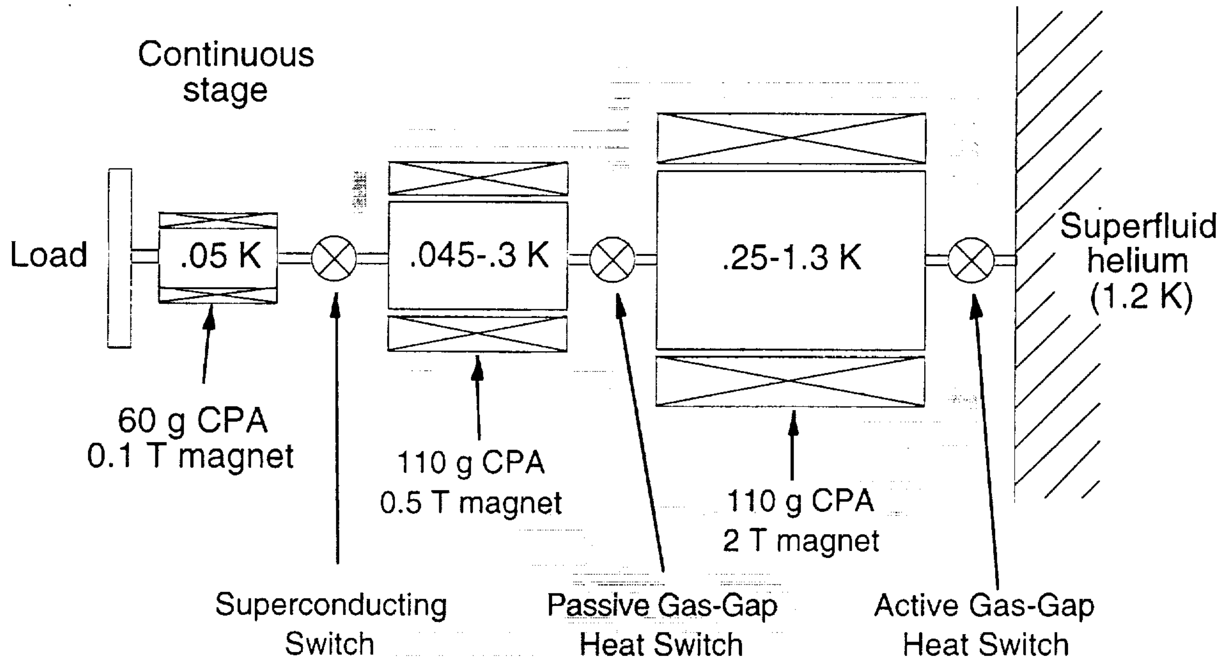

Figure 1. Schematic of a three-stage CADR with nominal design parameters.

Because this process does not interrupt cooling at the load, the recycling of each stage can be done frequently. Practical limits for how quickly a complete cycle can be performed are imposed by the overhead of opening/closing heat switches and magnetizing/demagnetizing the salt pills, and by the need to limit thermal gradients and eddy current heating within the salt pills (to maintain high efficiency). For a three- or four-stage ADR, a 1-2 hour cycle period is reasonable. This is an order of magnitude less than the typical hold time requirement for single-shot ADRs, so the CADR requires a proportionally smaller amount of refrigerant for each stage. Furthermore, the magnetic field requirements for each stage scale with the maximum temperature each one must reach, so while the magnets for all stages are quite small, those for the lowest temperature stages are nothing more than coils of a few thousand turns. The result is a considerable mass reduction for the same cooling power over a conventional ADR. We estimate that a four-stage CADR capable of 10 μW of cooling at 50 mK using a 6-10 K heat sink would have a cold mass of about 10 kg, including magnetic shielding.

DESIGN

The success of this concept rests on having heat switches that collectively span the operational range of the CADR, from the operating temperature up to the heat sink temperature. Each switch must have high thermal conductance in the closed, or "on", state since this governs the rate at which each stage can be recycled, and that in turn determines the cooling power of the CADR. It is also important to achieve the lowest possible off conductances in order to minimize the number of stages needed and the parasitic heat loads on each stage. At the outset, we derived

requirements for the on conductance based on two assumptions: first, an equal amount of time is allotted for each stage to be recycled, and second, the gradient across each switch during a recycle operation is no more than 10% of the absolute temperature. The latter is an important criterion for all stages in that smaller gradients translate to higher thermodynamic efficiency, but it is absolutely critical for the switch attached to the continuous stage. The reason is that when the continuous stage is recycled, the second stage is demagnetized to the lowest temperature that any component ever reaches. The temperature it must reach is the operating temperature minus the gradient across the switch. Since the zero-field entropy of the refrigerant is a strong function of temperature in the 50 mK range, a smaller gradient corresponds to a significantly larger entropy capacity and consequently lower mass required for the second stage.

Given these two assumptions, the on conductance of each heat switch can be estimated as follows. For a four-stage CADR, the average heat flux into the continuous stage of 10 μW requires a transfer rate of at least 40 μW out of the stage when it is being recycled. Using a 5 mK temperature gradient (at 50 mK), the on conductance of the heat switch must be at least 8 mW/K. For the other stages, the required heat flux scales linearly with the temperature at which the heat is transferred. But since the gradient allowed across the heat switch also scales with temperature, the on conductance requirement for each heat switch is the same 8 mW/K.

Our present design for a three-stage CADR operating with a superfluid helium bath at 1.2 K uses a superconducting tin switch between the continuous stage to the second stage, and ^{3}He gas-gap switches to connect the second stage to the third, and the third stage to the helium bath. The superconducting switch is activated by a small pair of Helmholtz coils that produce a field perpendicular to the heat flow path. The gas-gap switch between the second and third stages is passively activated as described in [2]. The third stage's gas-gap switch is activated by a zeolite getter. Heating the getter above 12 K produces full conduction and cooling it below 9 K turns the switch fully off. It can be turned on within seconds and off in less than 1 minute. The operating temperature ranges of the switches are shown in Figure 1. The lower temperature limits are the thresholds below which the switches fail to have the required on conductance (for a 10 μW cooling power). The upper limits are chosen to maximize the cooling power of the ADR, and represent a compromise between minimizing the *average* parasitic heat leaks through the heat switches and maximizing the temperature at which these heat loads are absorbed.

For the salt pills which must produce cooling below 1 K, we use chrome potassium alum (CPA). Although CPA has an intrinsically lower entropy capacity than the more common ferric ammonium alum (FAA), it has several advantages. Its lower ordering temperature will ultimately allow the ADR to operate in the 15-20 mK range, its higher melting point eliminates concerns over handling and storage in the laboratory, and we can use automated machining techniques to produce thermal buses out of copper since copper does not react with CPA. Figure 1 shows the masses and magnetic fields chosen for a 10 μW system. The cooling capacity of each stage must be larger than the previous one to account for extra parasitic heat loads and inefficiencies in the heat transfer processes. The salt and magnet parameters also reflect other concerns. For example, the second stage must have the most capable thermal bus since it must reach the lowest temperature in the system and at the same time accept heat at a relatively high rate from the continuous stage. We therefore elected to use a larger salt pill (with larger salt mass and larger surface area between the salt and thermal bus) with a smaller magnet. The same salt pill is then more than adequate, with a larger magnet, for the third stage.

For a four-stage CADR that would operate with a helium bath at 4.2 K or with a cryocooler at 6-10 K, gadolinium gallium garnet (GGG) would be a reasonable choice for the fourth stage. It is a readily available material and its magnetic field requirements can be met with standard (NbTi) superconducting magnet technology or with a Nb_3Sn magnet depending on whether the eventual heat sink temperature is above about 6 K. Part of our development effort is to produce and evaluate more advanced materials such as mixtures of Dy and Gd gallium garnets[3,4], and iron-

doping of these garnets. These have the potential to significantly reduce the magnetic fields needed and hence the mass of the magnet and any necessary shielding.

THREE-STAGE DEMONSTRATION UNIT

We have assembled a three-stage ADR in order to conduct a demonstration of continuous cooling. The CADR consists of components that were developed for earlier demonstrations of heat switch techniques and two-stage heat transfer experiments. Therefore they are not necessarily as capable or as large as those needed to meet our 10 μW at 50 mK performance goal. The most notable deficiencies are that the continuous and second stages use salt pills containing only 42 grams of CPA, and the superconducting tin heat switch has an on conductance of only 2 mW/K at 50 mK. The heat switch in particular will reduce the maximum cooling power by about a factor of four, but still the demonstration allows us to test control algorithms and measure such factors as thermodynamic efficiency that will help us optimize the final design. The third stage, on the other hand, is an engineering unit ADR left over from the X-Ray Spectrometer instrument[5]. It is oversized for the system, but we compensate for this by reducing the magnetic field used to achieve approximately the same cooling capacity as the smaller salt pill will have.

The demonstration CADR is shown in Figure 2. The continuous stage is pictured in the upper right and consists of a 42 g CPA salt pill, a 0.1 T magnet and 0.5 mm thick layer of AD-MU-80 magnetic shielding. Both the magnet and shielding are attached to the salt pill. The stage is

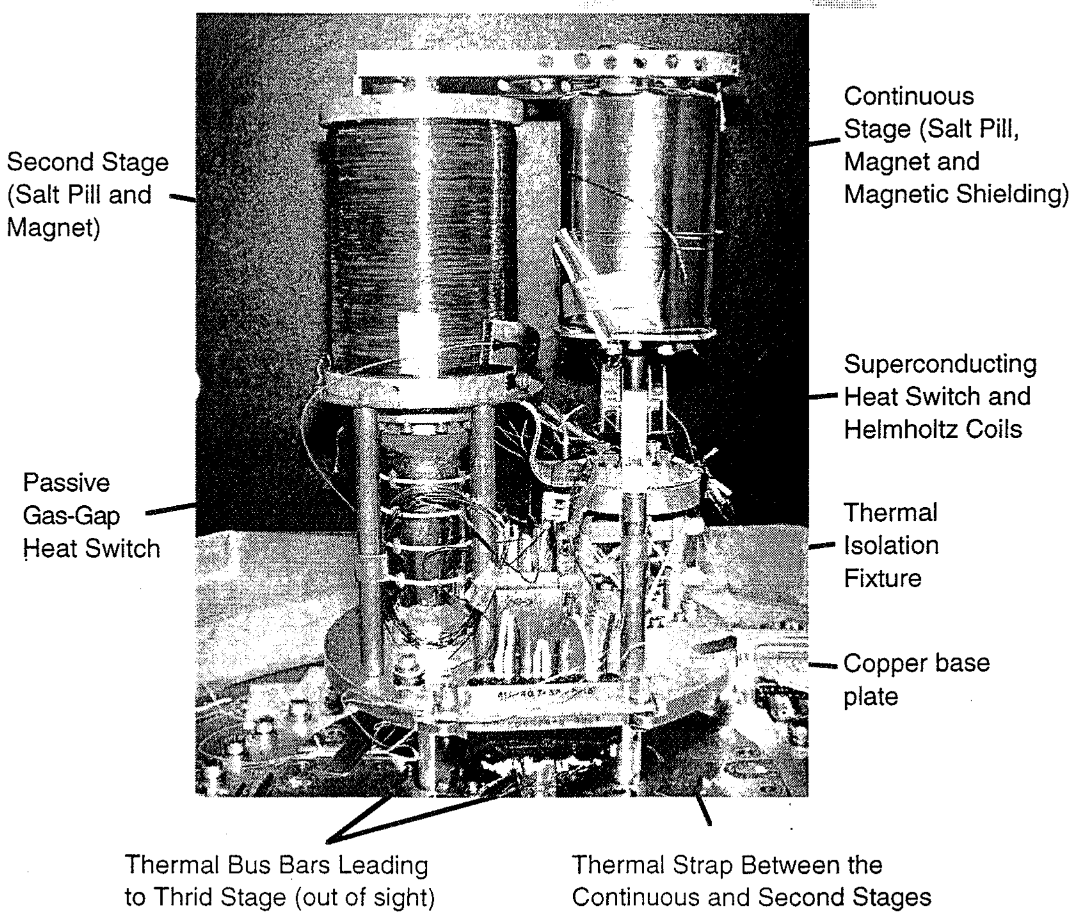

Figure 2. Three-stage CADR.

physically supported by the superconducting heat switch and a thermal isolation stand mounted to the third stage. A copper thermal strap (99.999% pure copper with an A/L of 0.04 cm; annealed at 550 °C for 4 hours) connects the base of the heat switch to the second stage. The second stage, shown on the left, consists of a 42 g CPA salt pill that is physically supported by its passive gas-gap heat switch off a copper plate which is attached to the thermal bus bars of the third stage. The second stage's 0.5 T magnet is also supported by this plate. This magnet is not shielded in order to assess how significant the magnetic interference between stages will be. The third stage is located out of sight in the bore of a 2 T magnet which is immersed in the liquid helium bath. The 730 g FAA salt pill is thermally linked to the liquid helium through a gas-gap heat switch.

The two CPA stages fit easily within a 1.3 K radiation shield whose dimensions are 11 cm diameter by 20 cm length. Their mass is approximately 500 g. There is sufficient room that as additional salt pills are fabricated, we will be able to package three, and possibly even four, stages within the confines of the radiation shield. This will result in a compact continuous refrigerator weighing less than 1 kg that can operate with a superfluid bath, or in the case of four stage, with a 4.2 helium bath.

OPERATION

In this section we discuss the details of how the multi-stage system is cycled to produce continuous cooling. For convenience, the three ADR stages will be designated S1, S2, and S3, with the continuous stage being designated as S1, and their respective heat switches HS1, HS2, and HS3.

The electronics used to control the CADR consist of three magnet power supplies, a 10-channel resistance bridge, and two power supplies for the superconducting and gas-gap heat switches. The magnet supplies have 3 A capability, which is more than necessary to reach full field on each magnet, and fine voltage control. The resistance bridge provides continuous readout of 10 channels. It is a custom box that was developed for the X-Ray Spectrometer mission. The rapid readout of all channels helps diagnose and characterize performance, but it is not necessary. Since the load is the only temperature that must be controlled to high precision, it is the only temperature that needs to be readout out continuously with a high-quality bridge. All other temperatures could be read out with less precision using a multiplexed bridge.

The control software consists of three identical digital temperature controllers and a separate routine which monitors the status of each stage and takes action to recycle each one as needed. All four routines run concurrently and on a single computer. The recycling routine works mainly by communicating with the temperature controllers to adjust target temperatures and maximum magnet ramp rates. The only direct actions it can take are to turn the heat switches on and off. The digital temperature controllers are not able to maintain the level of stability that we have previously demonstrated[6] when using an analog controller, but for the present development they afford much greater flexibility in operating the ADR in terms of imposing current and ramp rate limits, initiating control and pausing, etc. Ultimately, though, we will revert to using an analog controller at least for the continuous stage to demonstrate tight temperature control throughout the cycle.

Warm Start

The procedure for a warm start is straightforward. Once the helium bath is pumped to 1.2 K, all three stages are fully magnetized with HS1 and HS2 powered on. HS2 is passively on at this point. HS3 is then turned off and S3 is demagnetized to approximately 0.25 K. The rate is typically kept around 0.1 K per minute so that S1 and S2 are cooled efficiently. S3 is then demagnetized more slowly to a standby temperature of 0.2 K. When S1 and S2 cool below 0.25

K, S2 is demagnetized below the ADR's desired operating temperature. For present tests, this was in the range of 60-100 mK. The GGHS linking S2 and S3 will passively turn off as S2 cools below about 0.15 K. As S1 approaches the operating point, its temperature controller is engaged to begin fine temperature control. In this configuration, with HS1 still on, S1 is being actively cooled by S2 and therefore must be magnetized to maintain temperature. Control of the ADR is then transferred to a routine which begins recycling each stage as needed.

In cases where a significant heat capacity must be cooled, the initial demagnetization of all three stages may not bring the system all the way to its base temperature. As long as the second stage can cool below about 0.15 K, the third stage can be recycled while the other two stages remain cold. After S3 is brought back to low temperature, S2 can be recycled and used to cool S1 even further. If necessary this procedure can be repeated until S1 is cooled to the base temperature with sufficient magnetic field remaining.

Continuous Cycling

The periodic recycling of the ADR is also a straightforward process. The nominal operating mode involves monitoring the current in the continuous stage's magnet. Whenever it falls below a preset minimum, all three stages are recycled in sequence. If necessary, recycling of S1 can begin again before the recycling of S3 (or even S2) is complete. The controller also monitors the other two magnets and will immediately recycle those stages when necessary, even if this means interrupting a recycle operation in progress. This generally occurs in the first cycle or two after a warm start when the upper stages have less cooling power than normal, but it will also occur when the heat load on the continuous stage approaches or exceeds a sustainable level. The controller's response is to accelerate the recycling rate of each stage by increasing the temperature gradient across each heat switch. In the case of high heat loads this will only be marginally successful because it also increases the parasitic heat load on the continuous stage. If the high heat load is temporary, the system will recover quickly. If the heat load remains above a certain threshold, the continuous stage will eventually demagnetize completely and temperature control will be lost. This threshold represents the cooling power of the ADR.

Figures 3 through 5 show the process of recycling each of the three stages, and Table I gives the parameters used to determine when and how each stage was to be recycled. Figure 3 shows the current and temperature of stages S1 and S2 when S1 is recycled. Initially, HS1 is off and S1 is being demagnetized as it absorbs an 8 μW heat input. When the current reaches it lower limit, S2 is cooled from its standby temperature of 0.12 K to S1's temperature (0.1 K). HS1 is turned on and S2 is cooled to 0.09 K. Now that there is a net heat flow out of S1, it must be magnetized to maintain constant temperature. When its current reaches an upper threshold, the process is reversed: S2 is warmed to 0.1 K, HS2 is turned off, and S2 can be returned to its standby state.

Table I. Control Parameters for the Continuous Cycling. Magnetic field values are averaged over the volume of the salt pill.

<u>Continuous Stage (S1)</u>	
Base temperature	0.10 K
Lower current threshold	0.6 A (0.045 T)
Upper current threshold	1.0 A (0.075 T)
<u>Second stage (S2)</u>	
Lower temperature for recycling S1	0.09 K
Upper temperature for recycling S2	0.275 K
Standby temperature	0.12 K
Lower current threshold	0.05 A (0.008 T)
Upper current limit	2.2 A (0.35 T)
<u>Third Stage (S3)</u>	

Lower temperature for recycling S2	~0.25 K
Upper temperature for recycling S3	2 K
Standby temperature	0.20 K
Lower current threshold	0.05 A (0.040 T)
Upper current limit	1.0 A (0.875 T)

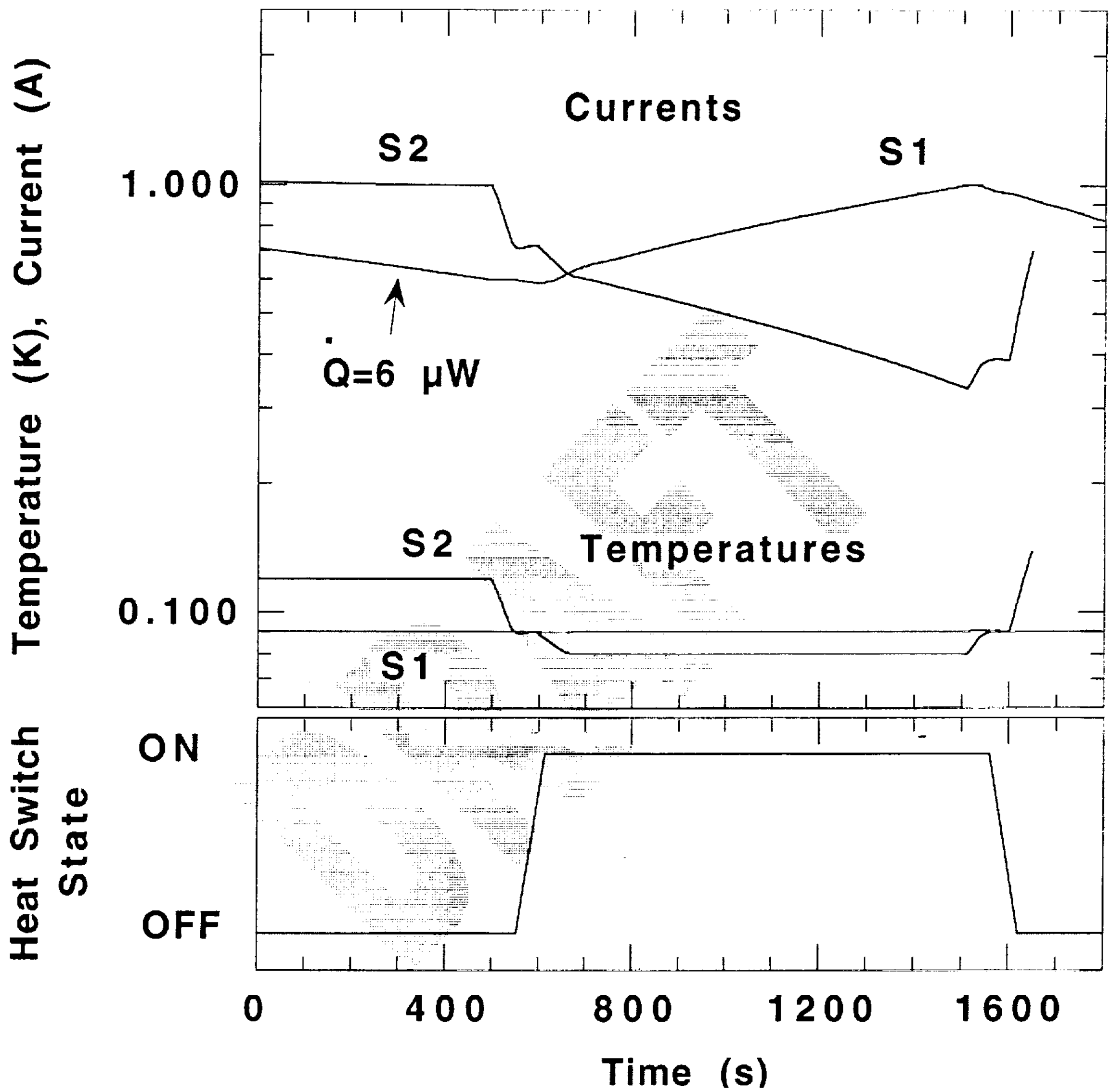

Figure 3. Temperature and current profiles while the continuous stage is recycled. The applied heat load during this cycle is 6 μW.

Instead, S2 is immediately recycled (Figure 4). The procedure is different than just described because this stage uses a passive heat switch. The first step is to magnetize S2 to raise its temperature to 0.275 K. The passive switch will begin to conduct when S2 warms above 0.15 K. At this point S3 is still warmer, but the conductance is low enough that the heat flow is negligible. Once S2 is warmer than S3, S3's temperature is periodically adjusted to obtain maximum heat conduction between the two stages. This adjustment reflects the fact that the heat switch's conductance depends only on the temperature of the colder end, and it is a strong

function of temperature in this range. Therefore, even though raising S3's temperature reduces the gradient across the switch, up to a point the conductance increases by a larger amount and produces a larger heat flow. This process continues as S2 is ramped to full field and then cools to 0.25 K. At this point, S2 and S3 are cooled to their respective standby temperatures. HS2 will passively turn off when S2 drops below 0.15 K, making it possible to recycle S3.

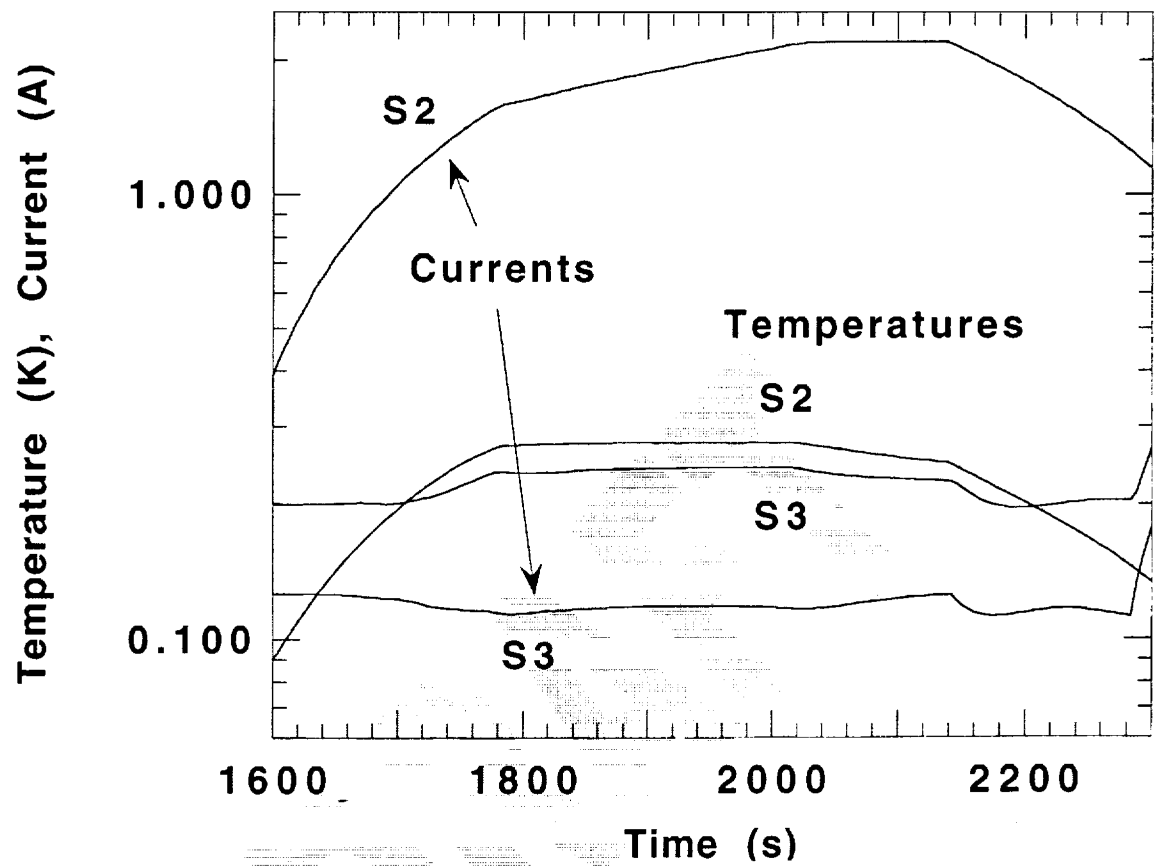

Figure 4. Temperature and current profiles while the second stage is recycled.

Finally, Figure 5 shows S3 being recycled. This process is the same as for single-stage ADRs. The stage is magnetized at a steady rate and HS3 is turned on when it warms above the bath. After it reaches full field, its temperature will relax toward the bath. When it reaches 1.3 K, HS3 is turned off and the stage is cooled to 0.2 K.

This process is repeated whenever the continuous stage's current drops below its lower threshold. The frequency depends on the applied heat load, but it can be as often as every 30 minutes. This is faster than we initially expected, largely because we can use higher ramp rates for the magnets and we have significantly reduced the heat switch transition times. As a result we are able to achieve higher cooling power per unit mass than anticipated. (Here could show multiple cycles and discuss the magnetic interference between S1 and S2).

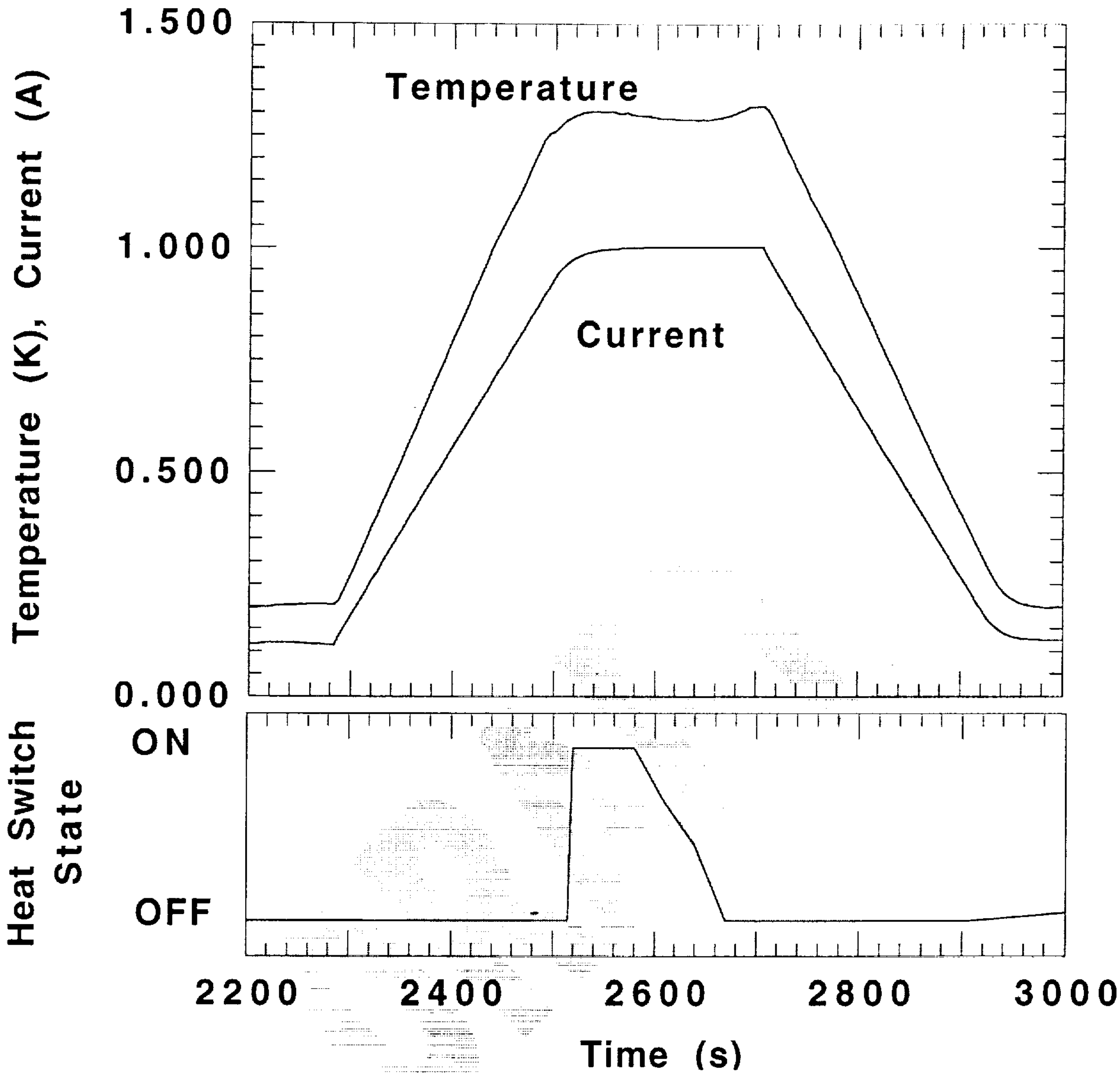

Figure 5. Temperature and current profile while the third stage is recycled.

Figure 6 shows the current and temperature profiles for all three stages during several cycles. In this case the base temperature was 100 mK and the applied heat load was changed from 2.5 μW to 5 μW at about the 50000 second mark. The increase is accompanied by a more rapid demagnetization rate for the continuous stage, and a shortening of the cycle period. At even higher heat loads, the continuous stage will begin recycling while S3 is being recycled, but this poses no problem for the operation. It is true that the parasitic heat load from HS3 will be absorbed by S2 while it is at its lowest temperature, but that load is small compared to the heat being transferred from S1 and it has very little impact on performance.

The only other feature of note is the magnet interaction between S1 and S2. Referring to the circled portion on the graph, as the second stage is magnetized, the demagnetization rate of S1 is more rapid than necessary to absorb the applied heat. As S2 is subsequently demagnetized, the demagnetization of S1 not only slows down, but reverses even though the stage is still absorbing heat. Once the magnetic field in S2 stabilizes, S1's demagnetization rate returns to the value expected for the applied heat load. The interference is not a particular concern except at the

highest heat loads where the drop in S1's current can prematurely trigger recycle event, even though it actually retains sufficient cooling power. The largest concern at present is the force exerted on the continuous stage magnet and shielding. Although we calculate it to be only a few pounds at most, the continuous stage is physically supported only by the superconducting heat switch and the torque could convceivably cause damage. In the future we will be adding magnetic shielding around the second stage magnet to eliminate the issue.

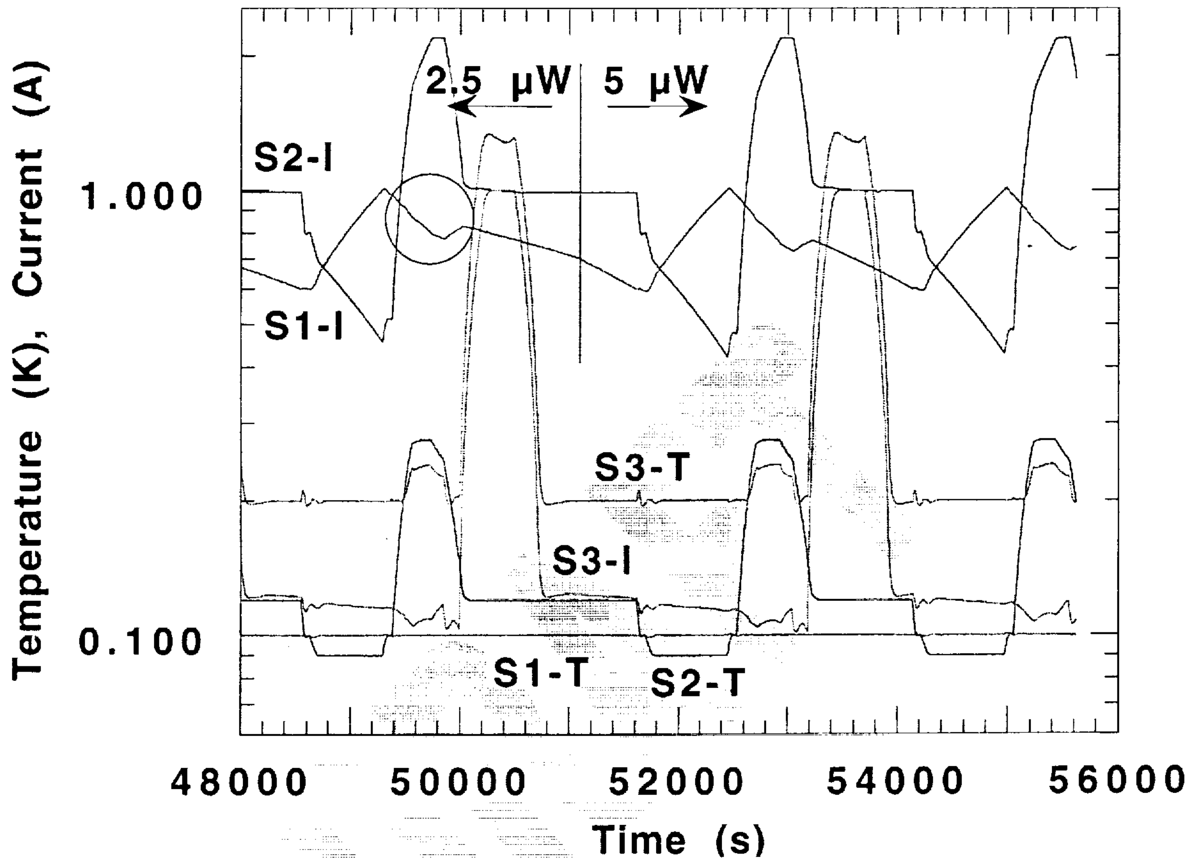

Figure 6. Temperature and current profiles for all three stages. At just after the 51000 second mark, the applied heat load was changed from 2.5 μW to 5 μW. The circled portion of the chart shows the effect of magnetic interference between the first and second stages.

PERFORMANCE

Cooling Power

Because ADRs are primarily heat storage devices, cooling power is not a well-defined quantity. That is, there is no unique relationship between base temperature and applied heat load. Rather, by adjusting the demagnetization rate, ADRs can accommodate quite large instantaneous heat loads, up to the limits imposed by the finite thermal conductance between the heat source and the salt. So for ADRs it is necessary to consider average, or sustained, heat loads. Cooling power in this sense is still ambiguous for single-shot systems, but for the CADR we can define it as the maximum heat load that the system can reject and remain indefinitely at the target temperature.

Table II gives the cooling powers that have been demonstrated so far. At higher temperature where the conductance of the superconducting switch is within a factor of two of the 8 mW/K goal, we are able to achieve the target cooling power of 10 μW. At lower temperature, the

reduced conductance lengthens the recycle time and causes too much of the second stage's cooling capacity to be used in absorbing the applied load. We have partially compensated for this by increasing the gradient across the switch when the continuous stage is recycled. But at lower temperature the second stage has too little cooling capacity fully recycle the continuous stage. Hence the hold time of the continuous stage, and its cooling power, drop off rapidly. The effect is severe enough that the present system is barely able to reach 50 mK even with zero applied heat load. For future efforts, increasing the heat switch conductance and using a larger second stage salt pill will alleviate the limitation on cooling power and base temperature.

Table II. Demonstrated Cooling Power versus Operating Temperature

T (K)	P (μW)
0.10	10
0.09	9
0.08	8
0.07	5.5
0.06	2.5

Efficiency and Heat Rejected to the Helium Bath

As yet we have not made careful measurements of the heat transferred as each stage is recycled and so are not in a position to evaluate the efficiency of each stage. However, it is possible to estimate the overall efficiency using the magnetic field profile of the third stage. Historically we have found that FAA is very well described by the ideal entropy function for a non-interacting spin system if one uses the effective magnetic field, $B_{eff}^2=B^2+b^2$, where B is the applied field and b represents a small internal field arising from the interaction of neighboring spins. For FAA, b=0.04 T provides the best fit to zero-field entropy data. Therefore we can calculate the entropy of the FAA just after it has been recycled, and just before it recycled again. The heat rejected to the bath is then $\Delta Q=\Delta S \bullet T_{reject}$, where ΔS is the difference in the two entropies, and T_{reject} is the average temperature of the salt as it transfers heat to the bath. For one cycle in which a 9 μW heat load is applied at 90 mK, we find ΔQ=0.663 J. The cycle interval was 42 minutes, giving an average heat rejection rate of 263 μW. An ideal system would have a rejection rate equal to the applied heat load times T_{reject} divided by 90 mK, or 130 μW. Thus the overall thermodynamic efficiency is on the order of 50%. The best that we could have expected for each stage, just based on the ratio of temperatures of the salt pills during each recycle event, is 89%, 88%, and 91%, or an aggregate efficiency of 71%. The difference is most likely due to thermal gradients within the salt pills causing the salt to absorb heat at lower temperature.

CONCLUSION

We have constructed a three-stage ADR that can achieve continuous cooling at temperatures down to 60 mK with high cooling power. At 60 mK the system can handle a sustained load of 3 μW, and 10 μW at 100 mK. Simple control algorithms are used to monitor the status of each stage and recycle them when necessary, cascading heat from the load up to a superfluid helium bath. The ADR's cooling power should be roughly independent of temperature, but in the present system the superconducting heat switch that links the two lowest temperature stages has an on state conductance that is a factor of four lower than desired. The salt pills used in this demonstration also have less refrigerant mass than desired. Additional components are being fabricated to remedy these deficiencies, and we anticipate that the resulting ADR will be able to achieve 10 μW of cooling at 50 mK. A three-stage system using these new components will be compact, occupying a volume of less than 2 liters, and weigh about 1 kg. In the short term we

will also be working to construct a four-stage ADR for use with a 4.2 K helium bath or a cryocooler.

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